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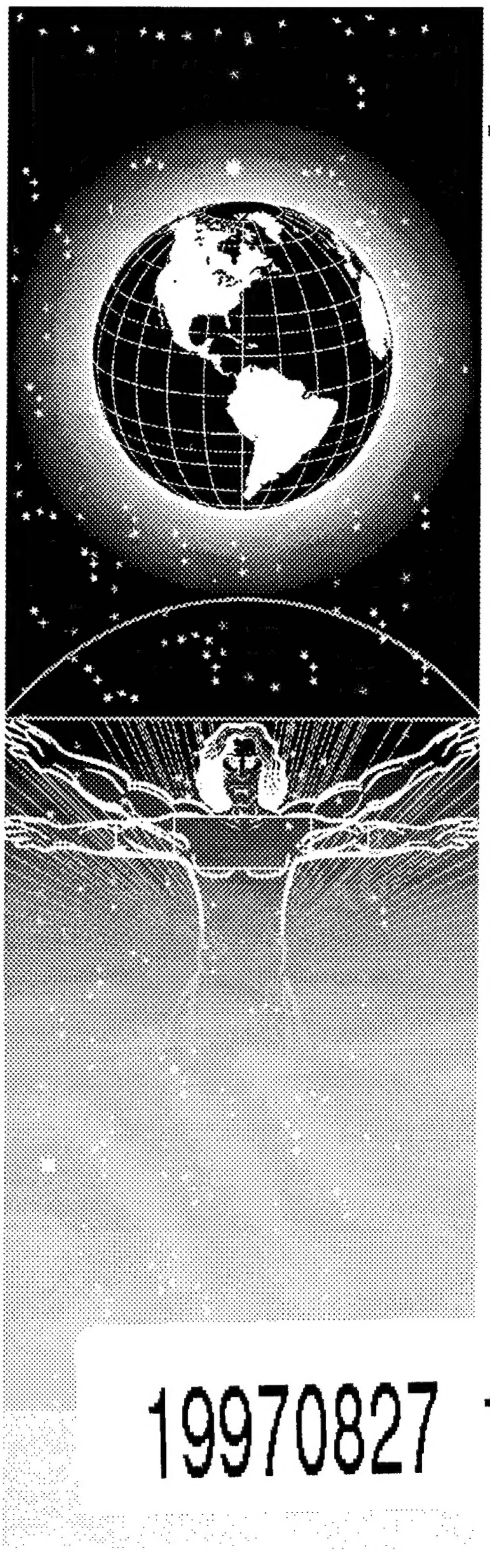

UNITED STATES AIR FORCE
ARMSTRONG LABORATORY

EEG-BASED CONTROL: NEUROLOGIC MECHANISMS OF STEADY-STATE SELF-REGULATION (U)

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This report has been reviewed by the Office of Public Affairs (PA) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nations.

The voluntary informed consent of the subjects used in this research was obtained as required by Air Force Instruction 40-402.

This technical report has been reviewed and is approved for publication.

FOR THE COMMANDER

/Kenneth R. Boff/

KENNETH R. BOFF, Chief
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Neural self-regulation is key to successful application of EEG-based control for advanced interface technologies. In the EEG-based interface examined, the magnitude of the steady-state visual evoked response (SSVER) served as a control signal. The SSVER was identified and monitored using non-invasive scalp electrodes and advanced signal processing technology. With biofeedback, subjects learned to increase or decrease the magnitude of their SSVER to an evoking stimulus. These responses were translated into commands that controlled the operation of a physical device or computer program.

The objective of this research was to identify some of the neurologic mechanisms involved with neural self-regulation. Using brain electroencephalographic (EEG) and evoked potential (EP) data, the character, timing and neuroanatomical significance of mental operations during task-related processes were examined.

14. SUBJECT TERMS
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PREFACE

This technical report documents the results of research performed by the Fitts Human Engineering Division, Crew Systems Directorate of the Armstrong Laboratory at Wright-Patterson Air Force Base, Ohio. This effort was accomplished under Work Unit ILIRCH32 and was funded, in part, by Armstrong Laboratory In-house Laboratory Independent Research (ILIR) Program funds. Lt Col Frank Fisher was Principal Investigator at the inception of this effort. Ms. Gloria Calhoun assumed program management responsibilities, upon his departure.

During the course of this research, Mr. Matthew Middendorf from Middendorf Scientific Services, Inc. provided systems analysis expertise. Ms. Darby Mahan, under the AFOSR High School Apprenticeship Program, compiled the results from the debriefing questionnaires. Several individuals working for Logicon Technical Services, Inc. (LTSI) were members of the research team: Mr. David Ingle (human factors), Mr. John Schnurer (electronics), and Dr. Victoria Tepe Nasman (neurophysiology). Dr. Nasman, in particular, was a key contributor and provided valuable technical insight from the project's inception. Much of the documentation contained herein was drawn from her work while she was employed with LTSI.

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INTRODUCTION

After nearly three decades of experimental and clinical research in the use of operant conditioning and biofeedback, it is now well-established that human beings can learn to self-regulate various aspects of their own brain electrical activity (Travis, Kondo and Knott, 1975; Plotkin, Mayer and Loewy, 1976; Pressner and Savitsky, 1977; Kuhlman, 1978; Fehmi, 1978; Elbert, Rockstroh, Lutzenberger and Birbaumer, 1980; Roger and Galand, 1981; Finley and Johnson, 1983; Rockstroh, Birbaumer, Elbert and Lutzenberger, 1984; Miltner, Larbig and Braun, 1986). Controlled experimental studies also provide convincing evidence that learned and voluntary self-control of electroencephalographic (EEG) or evoked potential (EP) activity can be achieved as a real and nontrivial phenomenon, rather than as the result of artifactual or peripheral mediation (Rosenfeld and Hetzler, 1978; Elbert et al., 1980; Roger and Galand, 1981; Finley, 1983; Finley and Johnson, 1983).

Since the mid-1980s, a number of different methodologies have been tested to examine the possibility that brain electrical signals might be used to control or communicate with physical devices. Preliminary efforts have been quite successful in demonstrating control and communication by self-regulation of alpha/beta frequency activity (Elder, Lashley, Kedouri, Regenbogen, Martyn, Roundtree, and Grenier, 1986) and sensori-motor (SMR or mu) rhythms (Wolpaw, McFarland, Neat, and Forneris, 1991). Self-regulation of the steady-state visual evoked response (SSVER) has also been used in the Alternative Control Technology Laboratory of the Armstrong Laboratory to achieve EEG-based control of the roll axis of a flight simulator (Junker, Schnurer, Ingle, and Downey, 1989; McMillan, Calhoun, Middendorf, Schnurer, Ingle, and Nasman, 1995), the operation of a functional electrical stimulator (rehabilitation exercise device; Calhoun, McMillan, Morton, Middendorf, Schnurer, Ingle, Glaser, and Figoni, 1995), a computer-based task to change the fill color of a displayed square to match the color of its border (Nasman, Ingle, and Calhoun, 1995), and the selection of switch icons (Calhoun and McMillan, 1996).

As subjects achieve expertise in performing these tasks, they find it increasingly difficult to describe or explain their own mental strategies for SSVER self-regulation. Increasing expertise seems to involve greater automaticity, such as subjects who report only that they "think left" or "think right" or those who report that their SSVER changes "almost automatically" in response to task requirements. This is not unlike how one might describe one's mental strategy for achieving a simple arm or head movement. With the exception of such anecdotal comments, demonstrations of neural self-regulation have generally failed to address the question of what neuro-cognitive mechanisms underlie the reported phenomena.

With the increased emphasis on applying neural self-regulation capability as a "direct brain interface", there is an increased need to understand how neural self-regulation is accomplished. It is necessary but not sufficient to conclude that the control of brain electrical activity can be accomplished by nontrivial or direct mediation. Applied designs must take into account those neuro-cognitive phenomena that support or hinder successful neural self-regulation. It is therefore necessary to identify and describe its mechanisms as precisely as possible. In addition, it is necessary to identify by what strategies operators learn and manage neural self-regulation, the importance of control signal feedback, in what experimental and applied tasks these skills may be most successfully and efficiently applied, and how to maximize signal quality by effective electrode placement, application, signal recording and acquisition.

OBJECTIVE

This research was directed towards examining the nature of brain electrical events that take place during the self-regulatory effort. Although our observations were shaped both by the specific character of our recording and control methodology, it is believed that the results will provide researchers a better understanding of various neuro-cognitive events and strategies that support or hinder neural self-regulation.

The specific objective of this research was to identify task and system event-related changes in brain electrical activity during SSVER self-regulation. We have approached this goal in two ways. First, two pilot studies were conducted to examine in what way, and at what sites, the SSVER is altered at the level of the scalp such that its resulting recorded measure is either "enhanced" or "suppressed" during self-regulation tasks. Second, a more comprehensive experiment was conducted to observe any changes in recorded topographic EEG data that might suggest primary or secondary effects of neural self-regulation on sensory or cognitive/attentional information processing. Taken together, these efforts represent an important first step toward the validation of a selected methodology, toward the sound application of its related tasks and systems, and toward the development of successful protocols for training and use (Nasman, 1996).

The following will provide a brief description of the system design employed in this research, along with summaries of the two pilot studies. Next, the topographic evaluation will be reported. The majority of the report is geared towards documenting the task designed for the latter study.

SSVER SELF-REGULATION: SYSTEM DESIGN

Studies at the Armstrong Laboratory have focused on the human's ability to voluntarily control EEG responses to sinusoidally modulated light (McMillan, et al., 1995). The experimental apparatus simultaneously controls the frequency of the evoking stimulus and provides the user with feedback on the strength of the EEG response at that frequency. The current system (Figure 1) uses fluorescent lights partially modulated at 13.25 Hz (26% depth of modulation) to evoke a steady-state response in the visual cortex. The signal used for control is the amplitude at 13.25 Hz of the bipolar (differential) SSVER recorded with gold cup electrodes between occipital sites O1 and O2 (left and right visual cortical hemispheres, respectively, according to the 10-20 International System for surface electrode placement; Jasper, 1958). The EEG signal from the scalp electrodes is amplified and then synchronously processed by a lock-in amplifier system. The lock-in amplifier provides a continuous measure of the magnitude of the 13.25 Hz SSVER component of the EEG signal. The magnitude of the response is provided to the subject feedback display and the task control algorithm.

Use of the SSVER amplitude as the control signal has been applied to several types of tasks in our laboratory (Calhoun and McMillan, 1996). In each of the task paradigms investigated, two types of feedback are provided. First, changes in the task state, as a result of the EEG-based control, can be observed. Second, near real-time feedback on the amplitude of the SSVER is provided in a separate display element.

To date, only one-dimensional control has been attempted. This involves translating the SSVER amplitude into a binary control signal. The control logic employs threshold and duration requirements to permit stable control of an external device despite variability in the operator's SSVER control. One implementation produces a control output when the SSVER remains above or below experimenter-specified thresholds for 75% of the samples in a one-half second interval. These settings require the operator to produce sustained changes in the SSVER; however, brief SSVER fluctuations do not interrupt task control. The threshold, duration and percentage parameters are adjustable for individual subjects and for specific device applications.

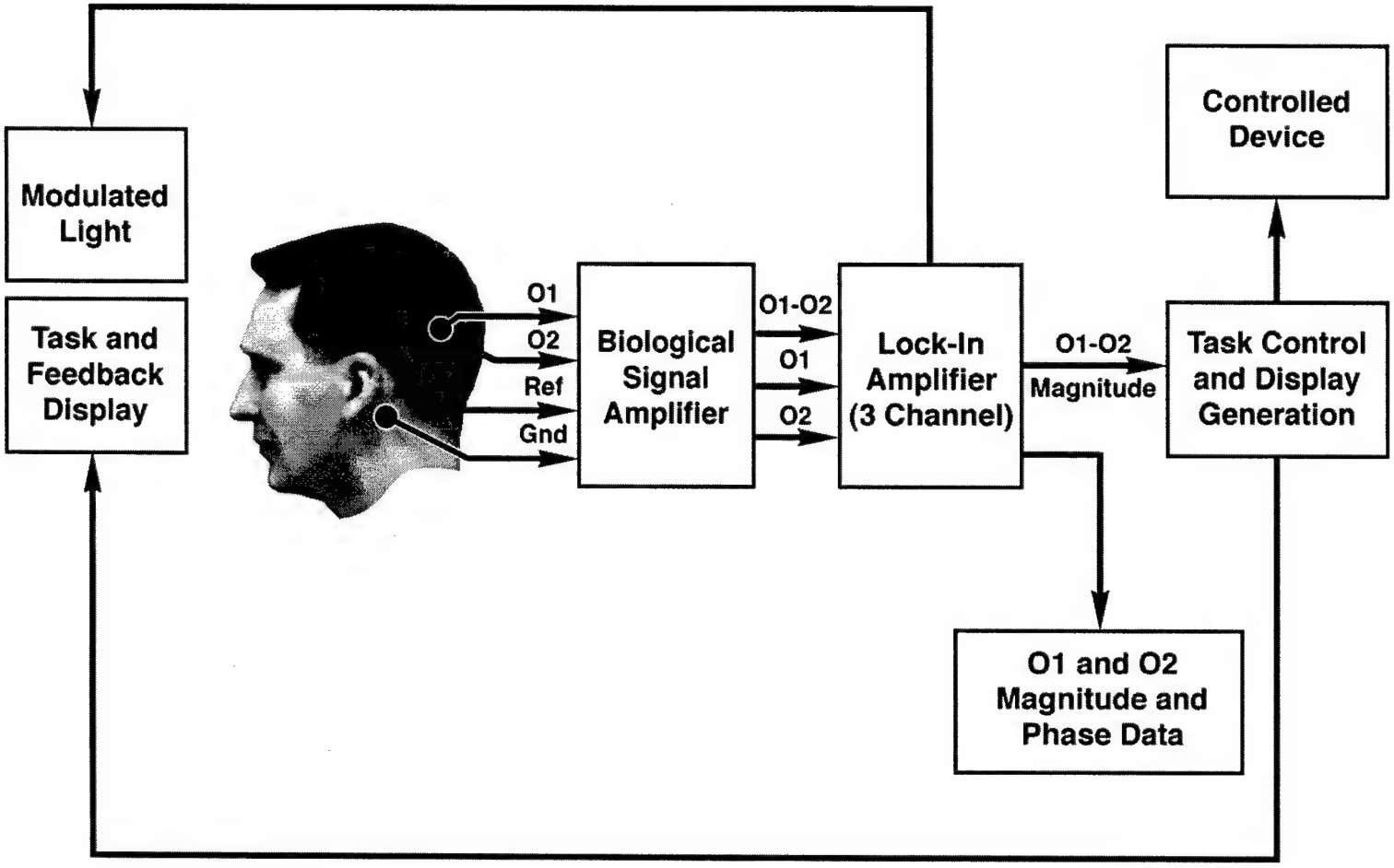

Figure 1. Illustration of EEG-based control using steady-state visual evoked response self-regulation.

PILOT STUDY 1
SSVER SELF-REGULATION AS A FUNCTION OF ELECTRODE SITE

Purpose

The purpose of this pilot study was to consider the question of whether the SSVER might be recorded from multiple scalp sites, rather than strictly from its traditional source as a signal derived from the occipital scalp (Ingle and Nasman, 1994). There is little reason to assume that SSVER self-regulation should be limited in its basis, or in its effect, to the sensory cortex. For example, learned volitional control over sensory processing might invoke operations related to perceptual-associative processing and/or high level attentional switching and control, and thus provoke related changes in brain electrical activity at other recording sites. This pilot study considered whether SSVER self-regulation might produce related changes that enable task control from anterior midline recording sites. Of particular interest were central and frontal midline scalp recording sites.

Method

Across two subject groups, a total of nine subjects were tested for their ability to enhance and suppress the SSVER beyond criterion thresholds in response to task commands (McMillan, et al., 1995). Each subject had received some previous training using the occipital SSVER to control the experimental task. A task display provided SSVER amplitude feedback and instructions to enhance or suppress the SSVER to the evoking stimulus. The SSVER was monitored on each trial from bipolar (differential) occipital (O1/O2), central (C3/C4) or frontal (F3/F4) electrode pairs (left mastoid as ground). The three recording configurations were independently calibrated. In Subject Group #1, each subject was tested with a randomly ordered series of six 68-second trials at each recording site. Similar procedures were used for Subject Group #2, except only four 52-second trials were presented at each recording site. All subjects were naive as to control site on each trial. Performance was scored as correct responses to task commands.

Results

On the average, control performance scores were higher for trials in which the SSVER was recorded at the occipital scalp. However, differences in performance among the three test recording sites failed to reach statistical significance in either of the two subject groups ($p > 0.3$). Subjects were able to achieve some level of control at all sites (Figure 2). On an individual basis, differences associated with recording site were apparently related to subjects' overall levels of ability. Statistically significant "best" or "worst" recording sites (frontal, central, or occipital) emerged only for subjects who failed to achieve better than 50% average correct responses for some sites (Figure 3).

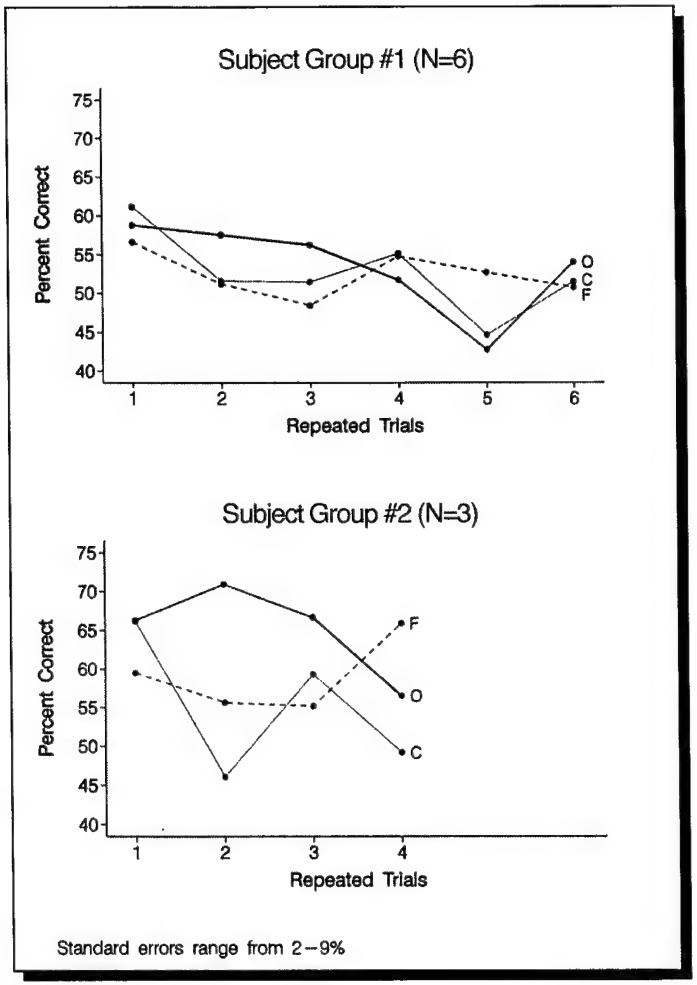

Figure 2. Performance (percent correct) on commands to enhance or suppress the SSVER beyond criterion thresholds with frontal (F), central (C), and occipital (O) electrode placements.

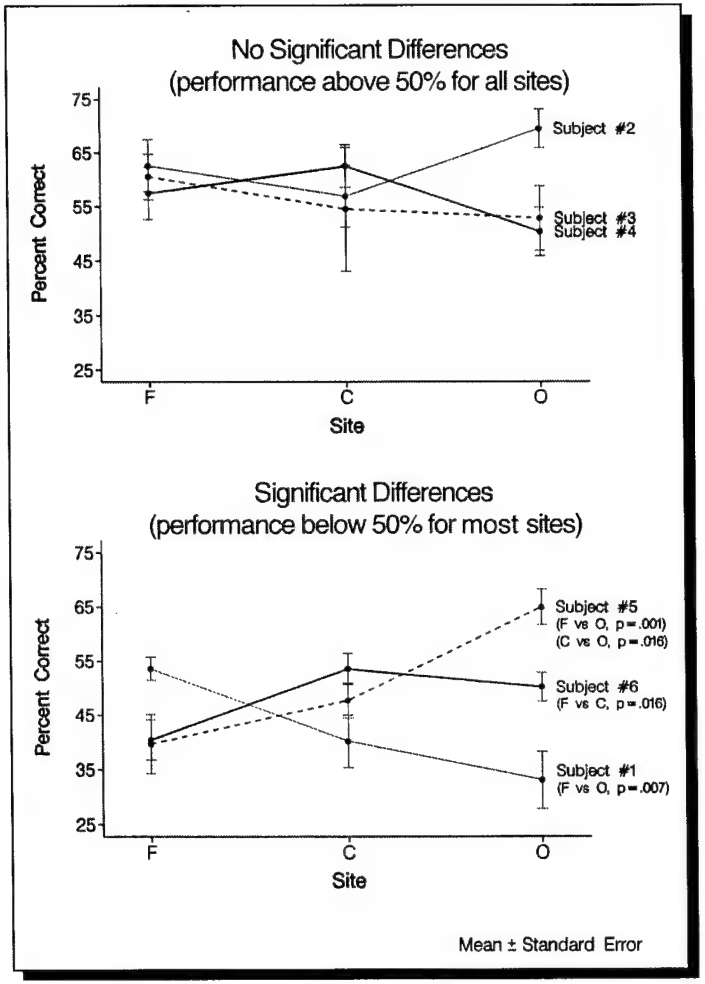

Figure 3. Differences between recording sites for subjects with "good" versus "poor" performance.

Conclusions/Discussion

These preliminary results suggest that SSVER self-regulation may involve neural processes not limited to those traditionally accessed over the occipital scalp, and that trained individuals may also achieve volitional control over related activities at the anterior midline. The data show that individual subjects can generally achieve varying degrees of control at frontal, central, and occipital recordings sites, that is, effective and comparable control can be achieved at locations other than occipital. It still needs to be determined what phenomena are responsible for control, for example, at frontal versus occipital sites. Perhaps the changes responsible for frontal control are merely more distant (volume-conducted) presentations of the changes that support occipital control. Another possibility is that the changes responsible for frontal control are in some way prerequisite (e.g., attention-related) to changes in the occipital sites. The results may also be influenced by which electrode site was used in the initial training or the accuracy of the calibration procedure. If further research demonstrates that control can be reliably achieved at multiple sites, it is possible that this capacity can be harnessed to implement multi-dimensional control.

PILOT STUDY 2
SSVER SELF-REGULATION:
EXAMINATION OF AMPLITUDE VERSUS PHASE

Purpose

The majority of biofeedback research has focused on the control of biological signal amplitudes, while little work has been done on the control of biological signal timing. However, there are basic studies which indicate that both the amplitude and phase of the brain steady-state evoked response are sensitive to attention and response preparation (Rockstroh, Mueller, Elbert, and Makeig, 1994) and cognition (Wilson and O'Donnell, 1986). SSVER amplitude reduction and phase lag have also been observed in association with increased regional (e.g., frontal) cortical activity related specifically to heightened visual attention (Silberstein, Ciorciari, and Pipingas, 1995).

The SSVER-based control signal in the present system is derived as a bipolar (differential) measure of occipital activity between hemispheres. Because the EEG data is acquired differentially, subjects can change the amplitude of the SSVER by self-regulating: (1) the relative amplitude of SSVER activity at the two recording sites, (2) the relative timing (phase) of SSVER activity at the two recording sites, or, (3) a combination of both signal characteristics (see Figure 4). The purpose of this pilot study was to examine in what ways SSVER activity is altered at the level of the scalp such that the resulting control signal is either enhanced or suppressed (Nasman, Ingle, and Schnurer, 1994).

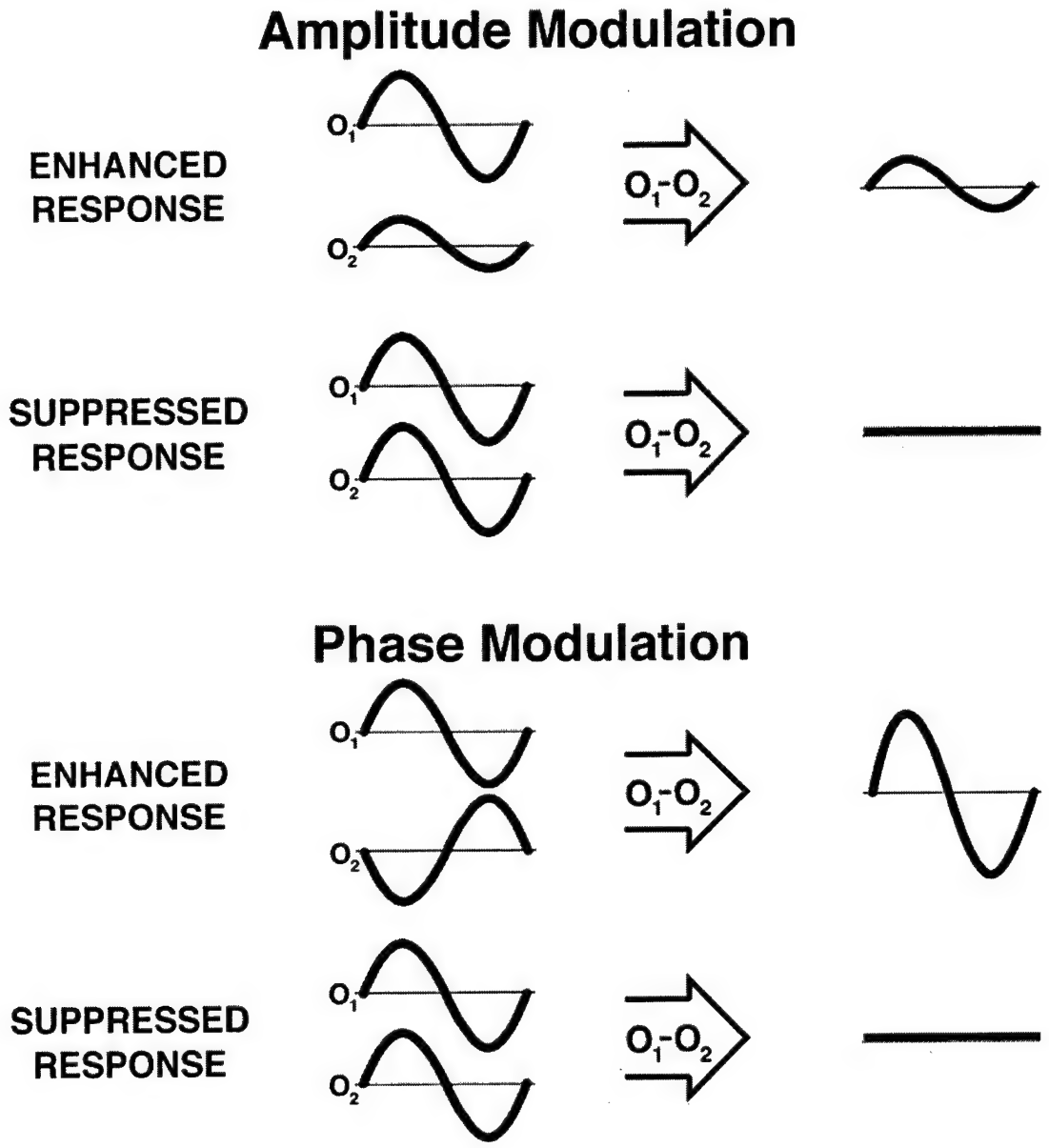

Figure 4. Illustration of the two possible mechanisms for self-regulating the steady-state visual evoked response, recorded with bipolar techniques.

Method

Four trained subjects received on-line bipolar SSVER amplitude feedback and a randomly ordered series of task commands to enhance or suppress their SSVER to a modulated light stimulus. Matched amplifiers were used to acquire monopolar (single site) and bipolar (differential) signals over the left and right occipital scalp (O1/O2, left

mastoid as ground). Each subject performed SSVER self-regulation in twelve repeated 50-second task trials. Both monopolar and bipolar signals were simultaneously recorded across the occipital midline to determine whether the control signal was regulated as a function of hemispheric differences in SSVER phase and/or amplitude.

The bipolar SSVER signals for each subject were reviewed to select several two-second epochs that represented sustained, task-related periods of SSVER enhancement and suppression. Monopolar data from the left and right occipital sites for the corresponding epochs were ensemble averaged and compared with respect to phase and amplitude.

Results

Each of the four subjects tested showed evidence of phase-based control. A variety of control mechanisms, though, were evident in individual records (see Figure 5). SSVER suppression was associated with phase synchrony in the two monopolar channels, with occasional small and unsustained amplitude differences. SSVER enhancement was associated generally with a sustained or periodic unilateral phase shift ranging from 45-180 degrees in a single channel, and was occasionally *also* associated with sustained inter-hemispheric mean amplitude differences (20-50% signal range). The two subjects who showed the best and most reliable task performance also showed the most consistent and robust phase effects, whereas these same effects were evident but less distinct and less reliable for the two subjects who did not perform as well.

Conclusions/Discussion

By examining the O1 and O2 signals independently, several methods for self-regulating the bipolar SSVER were evident. However, our two most proficient subjects tended to modulate the differential SSVER amplitude primarily by varying the relative transport delay or processing of sensory information at the two sites. (Data from one of these subjects is shown in Figure 5b.) This may possibly reflect the synchrony or asynchrony of firing the underlying neural generators of the EEG at specific scalp locations. To further examine the relationship between inter-hemispheric differences in phase and amplitude during SSVER self-regulation, additional data is required.

These results also suggest that an alternative control algorithm be examined. If regulation of response amplitude plays a secondary or modulatory role in SSVER self-regulation, then use of a phase-based control algorithm may be more optimal. Subjects may achieve more reliable and precise control if the algorithm is designed to employ phase information only. However, it is also possible that the availability of both components is important to some subjects, or at different points in the learning process. Additionally, it would be interesting to examine if SSVER self-regulation can even be accomplished with monopolar recording of the control signal.

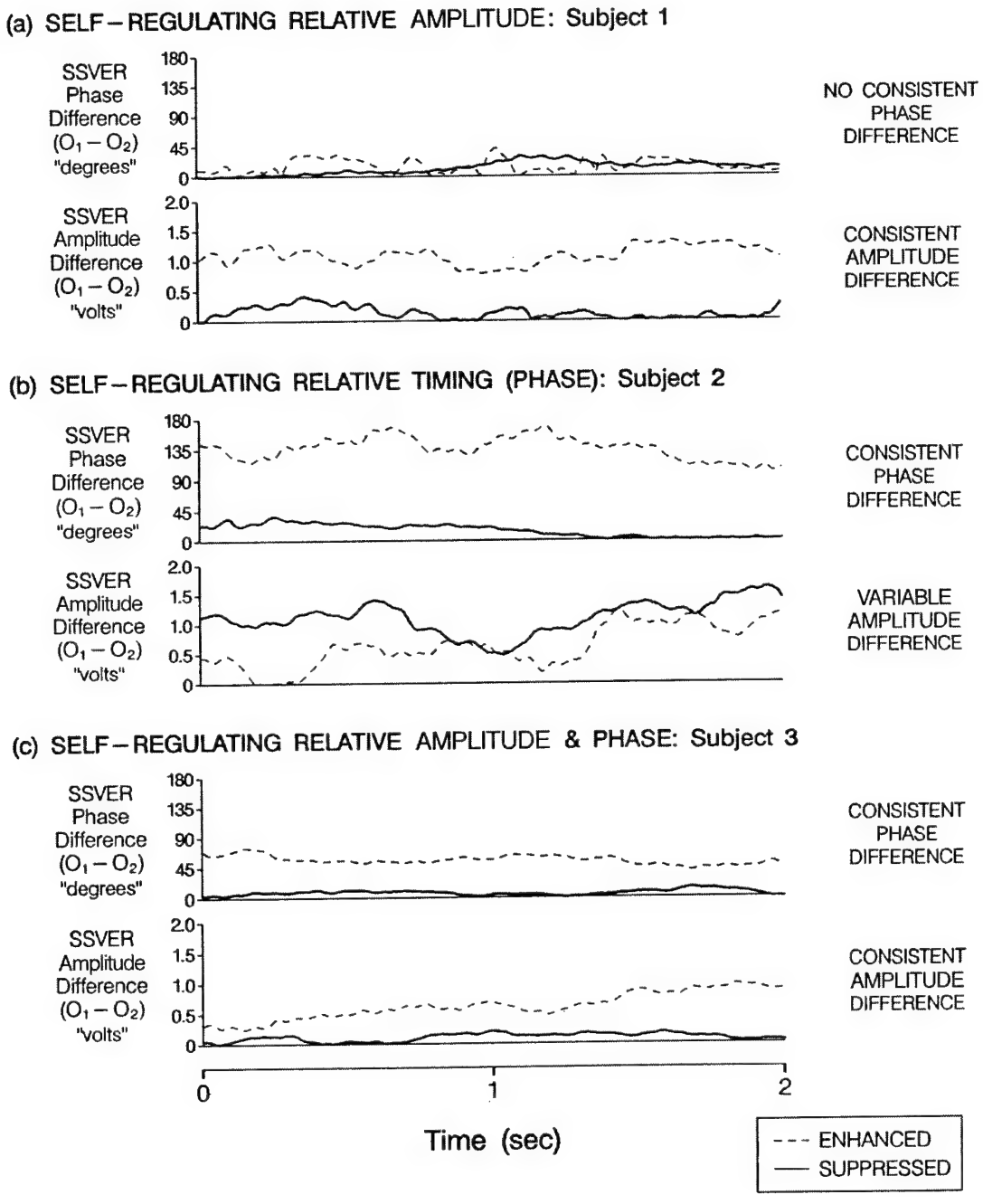

Figure 5. Examples of three control strategies for self-regulating the steady-state visual evoked response. (Subject 2 actually shows a reversed control amplitude difference between enhanced and suppressed segments, but the phase difference is so large, it makes counter amplitude effects negligible.)

MAIN STUDY
SSVER SELF-REGULATION: TOPOGRAPHIC EFFECTS

Purpose

The second pilot study reported herein shows that bipolar SSVER amplitude control can be mediated as a secondary effect of inter-hemispheric phase shifts. However, this finding is limited in the sense that it describes primary sensory cortical events that must be understood as effects of other, more fundamental processes (e.g., attentional regulation).

It may be argued that SSVER self-regulation can be viewed as a product of two stages of information processing: (1) feedback information processing, and (2) responsive alteration of neural state. In this study, EEG activity was recorded with respect to each stage of information processing by examining temporal records of EEG activity antecedent (2, above) or consequent (1, above) to critical task events (delivery of SSVER feedback and control signal changes). The task paradigm and feedback delivery employed were designed to provide sustained two-second epochs during which subjects self-regulated the SSVER beyond criterion amplitude thresholds. Here we address the need to identify and describe neuro-cognitive processes on the basis of observed changes in the topography of EEG components or dominant frequency bands during these epochs of SSVER self-regulation.

Method

Subjects. Three adult volunteers (one male and two females), ages 19-42 years, participated as subjects. Each subject had some level of previous experience performing SSVER control using other tasks tested in this laboratory. However, for the present experiment, every subject received instructions (Appendix A) and underwent a specific training protocol to achieve criterion performance on the experimental task. Subjects included in this study did not have any history of seizure disorder or visual loss.

Recording and apparatus. Subjects were seated facing a large white projection screen (see Figure 6). The experimental task display (17 x 23 inches) was presented on the screen at a viewing distance of 64 inches. Also reflected off the screen was a white light delivered from two fluorescent light tubes, sinusoidally modulated at a rate of 13.5 Hz (26% depth of modulation). The evoking stimulus was presented as a normally distributed light (peak value = 0.69 fL) across the height and width of the entire viewing screen, including the portion of the visual field in which the task feedback display was presented. The evoking stimulus was thus impossible to avoid while performing the task, but was sufficiently diffuse so as not to interfere with viewing the task display.

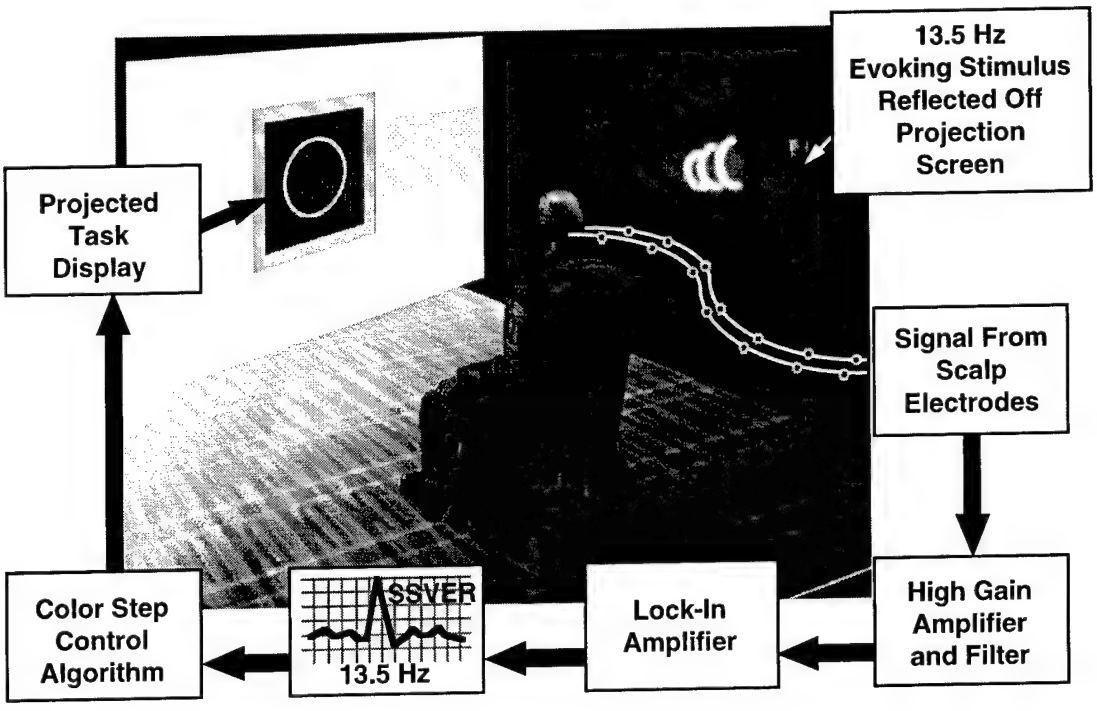

Figure 6. Schematic of experimental apparatus and setup.

The raw EEG control signal was acquired differentially using a standard bipolar montage, with electrodes placed at the left and right occipital scalp (O1 and O2; left mastoid as ground). The EEG was filtered (high pass at 0.3 Hz and low pass at 40 Hz) and amplified. The resulting EEG was then processed by a lock-in amplifier system to estimate the magnitude of the SSVER at the evoking frequency (13.5 Hz).

During the experimental session, scalpwide EEG (0.1-30 Hz) was recorded using an electrode cap (Electro-Cap, Inc.) with electrodes positioned at 19 sites across the scalp, according to 10/20 System placement. (SSVER recording/control electrodes were first positioned so as not to conflict with cap electrodes positioned over the occipital scalp.) EEG data acquisition for the electrode cap was managed by a Bio-Logic Brain Atlas (Bio-Logic Systems, Corp.), with signals amplified and 3 dB filter cutoffs set to pass signals between 0.1 and 30 Hz. Amplified signals were digitized at a rate of 200 Hz. Signals were referenced to linked earlobes. A sync (TTL) pulse marker train presented on the Oz channel was used to encode the EEG record to designate different task events:

(1) trial onset, (2) trial command type ("enhance" or "suppress" SSVER), (3) SSVER modification made (enhance or suppress step), (4) task progression, and (5) task completion versus time out. All electrode impedances were held below 5 Kohms.

Experimental task. Simulation timing, task control, and data recording were managed by a MicroVax II. Image generation was accomplished using an IRIS 3130. The experimental task and feedback display were designed to minimize the need for eye and head movements that can corrupt signals recorded by the brain mapping system. The task also provided definitive task segments to be used in the analysis of data. The computer-based task involved matching the fill color of a square with that of its border. Subjects changed the shade of the square's fill color by self-regulating and sustaining their SSVER above or below calibrated thresholds. The palette consisted of nine shades ranging from 100% blue to 100% red (Figure 7). The two outermost shades were reserved for "overshoot" conditions, to be described later. The three innermost shades served as initial fill colors for the square and the remaining shades served as "command" colors. The command colors were presented in the border area surrounding the square to inform the subject on whether the task required the SSVER to be enhanced or suppressed. The shades used in the color palette had a high degree of contrast to increase the likelihood that subjects would be able to tell when the fill and border colors matched, without closely examining the square's perimeter.

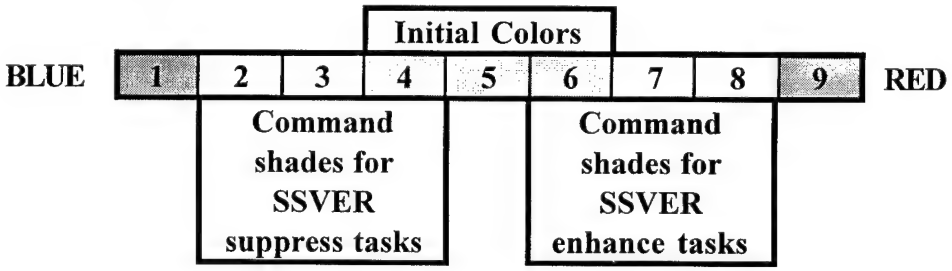

Figure 7. Illustration of color palette consisting of nine shades ranging from 100% blue (shade 1) to 100% red (shade 9). Shades 4, 5, and 6 were initial fill colors and shades 1 and 9 were reserved for overshoot conditions.

The threshold values used in the control logic were calibrated individually for each subject prior to testing and were represented in the displayed square as two fixed white circles. A black circle provided feedback to the subjects on the current amplitude of the SSVER in relation to the two thresholds. The diameter of the black circle changed, in real-time, in proportion to SSVER amplitude. Between thresholds, the diameter of the black circle changed linearly with respect to changes in the signal processed by the lock-in-amplifier; beyond thresholds, the circle diameter changed nonlinearly to prevent clipping of dynamic SSVER.

The black and white circles, respectively representing SSVER feedback and thresholds, are illustrated in Figure 8, along with how the task format changed corresponding to changes in the subject's SSVER amplitude. In Figure 8a, the subject's task was to enhance (increase) the SSVER amplitude to change the square fill color from blue to red. When the subject's SSVER amplitude had exceeded the "enhancement" threshold, the black circle was larger than the outermost white circle. Once the criterion time duration was met, the square's fill color stepped one shade closer towards the red end of the color palette. Keeping the SSVER amplitude above threshold for another criterion time duration resulted in another color shade step, such that now the square's fill color matches the border. To keep the fill color from progressing to an even deeper red shade (i.e., an overshoot condition), the subject had to suppress the SSVER amplitude below the enhancement threshold. If the black circle was between the two white circles, there was no change in the square's fill color.

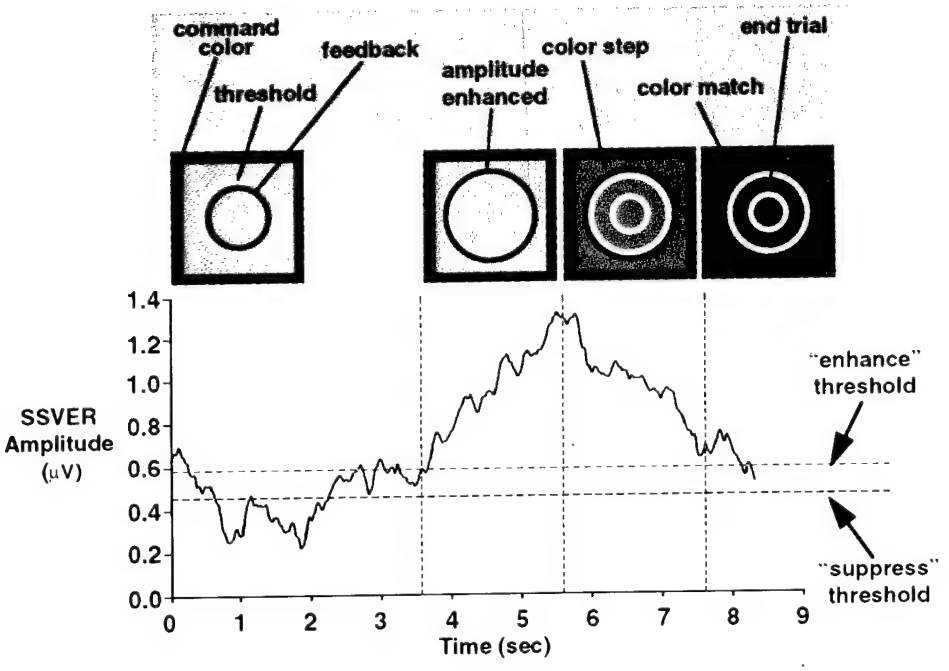

Figure 8a. Example time history of SSVER amplitude and corresponding task display sequence for trial requiring SSVER enhancement.

In Figure 8b, the subject's task was to suppress (decrease) the SSVER amplitude to change the square fill color from red to blue. When the SSVER amplitude had decreased below the "suppression" threshold, the black circle was smaller than the innermost white circle. Upon meeting the time duration criterion, the square's inner shade stepped towards blue. To avoid overshooting the commanded color, the subject's SSVER amplitude had to return above the suppression threshold after the fill and border colors matched.

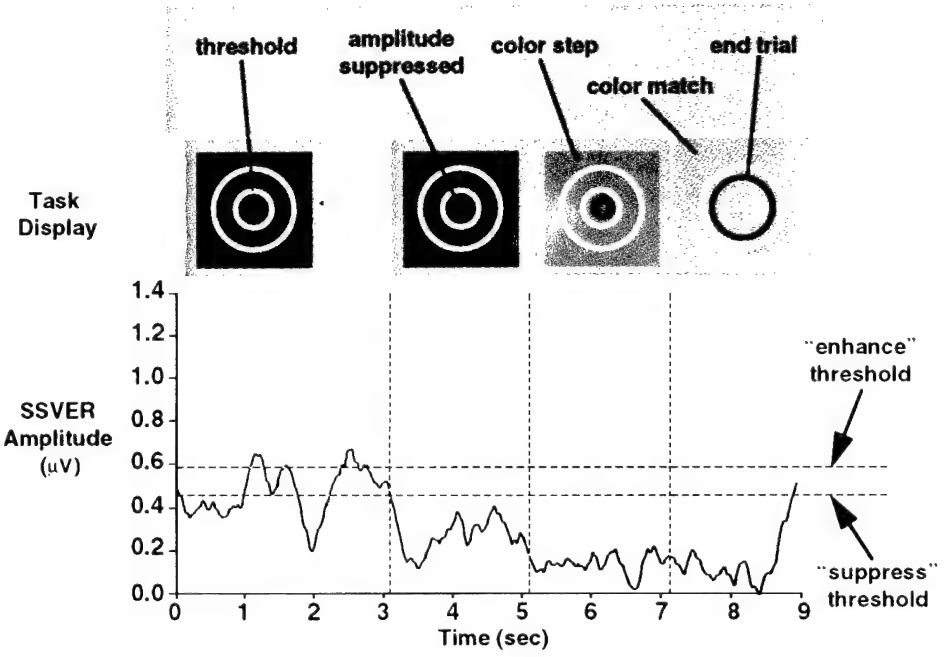

Figure 8b. Example time history of SSVER amplitude and corresponding task display sequence for trial requiring SSVER suppression.

Task procedures. In each trial, the subject began by viewing a simple white outline of the task display; this was presented for a duration of one second to allow the subject time to focus on the proper area of the projection screen prior to task onset. Next, the square was filled with one of the three (randomly selected) initialization colors from the middle range of the color palette. The circle representing SSVER amplitude was also displayed and updated in real-time for one second. This provided time for the subject to monitor the SSVER amplitude and view the initial color of the square, before

the area around the square's border was filled with the task command color. After this time period, and after the SSVER amplitude fell within the "neutral zone," the command color was presented in the border (set to a color shade away from the square's initial fill color; one or two steps on the color palette in training and two steps in the final experimental session). The subject's task was then to self-regulate his or her SSVER amplitude in the direction necessary to match the fill color of the square to the color of the square's border. Each change in color shade required maintaining the SSVER enhancement or suppression with respect to the experimenter-specified thresholds for the criterion time duration. If the SSVER amplitude temporarily crossed into the neutral zone between thresholds, the time clock was not reset. However, if the SSVER amplitude crossed over both thresholds, then the duration clock was reset to zero and a new criterion time period was begun.

Once a color match was achieved, the subject was required to stop the color-sequencing by reversing the SSVER amplitude towards the opposite threshold. If the subject failed to reverse the SSVER, the square's fill color continued to change to a deeper shade in the designated direction and "overshoot" the command color. In this case, the subject had to regain control over the SSVER signal and reacquire the color match by modifying SSVER amplitude in the opposite direction. The purpose for enabling dynamic control was to help prevent subjects from "gaming" the task. Rather than have subjects simply maximize or minimize their SSVER when they realized that the task required an enhancement or suppression, we wanted subjects to acquire the ability to exercise more precise and rapid control of the SSVER. With the possibility of overshooting the color, subjects had to maintain dynamic control of the SSVER amplitude.

Upon successful task completion, a reinforcing feedback display was presented consisting of multi-colored flashes. If the task was not successfully completed within the specified time limit, text was displayed which indicated that the trial timed out. After each series of twelve trials, a brief scoring display was presented which provided information on the number of successful trials (color matches), etc.

Trials were separated by a one-second pause. Trials were delivered in a block of twelve, each block separated by a two minute break. Between two and three blocks were presented in a daily session. In each block of twelve trials, six trials required SSVER enhancement and six trials required SSVER suppression.

Training sessions. Before participating in the final experimental session, involving scalpwide data collection, subjects had to achieve the following in training:

a) perform trial blocks in which all trials required two changes in fill color shade,

b) perform the trial within 30 seconds,

c) perform the trial with demanding control parameters (sustained SSVER with 100% of the samples past threshold for two seconds for each color shade step), and

d) at the above control parameters, successfully complete (match colors) 80% of trials, averaged over the trial blocks in each of three consecutive training sessions.

The very stringent control settings were required for the final experimental session to facilitate collection of scalpwide broad-band EEG during sustained periods of SSVER enhancement and suppression. To assist subjects in attaining this level of performance, initial training sessions required that only 80% of the samples in a one second interval meet the threshold criterion to produce a color step. Additionally, subjects were given 60 seconds to complete the trial and some trials only required one color step, as opposed to two color steps from the initial color shade. Both "one step" and "two step" color matches were used in training to force subjects to exercise precise control. This procedure also helped prevent subjects from learning an automatic response that may be inherently different from the dynamic control that is involved when the SSVER response requirements change from trial to trial.

As subjects acquired proficiency at these levels, the trial length was decreased and the control settings (duration and percentage requirements) were gradually increased. Subjects completed a minimum of ten training sessions, with the task requirements increasing in difficulty, as their performance improved. During the last few training sessions, all trials required two color steps to achieve a match.

Experimental session. In the final session, a broad-band recording system was used to collect scalpwide electrical activity during sustained periods of self-regulation of the SSVER. Each trial during the experimental session required two successive correct color steps to match the command color.

Besides the multi-channel electrode cap, subjects were instrumented for recording the SSVER control signal. Subjects were instructed to sit as still as possible and to minimize eye movement and blinking. Every subject was then tested in one baseline and two experimental conditions. In the baseline condition, subjects viewed the static outline of the task display for 30 seconds. This condition was included to allow the experimenter to observe on-line EEG and to address issues of subject cooperation and artifact. After obtaining baseline data, four blocks (12 task trials each) were presented, two blocks with each of two experimental conditions:

Condition 1: Procedures identical to those employed in the training sessions were used. The feedback was mapped consistently to changes in the amplitude of the SSVER control signal. These "experimental trials" were mapped as follows:

EXPERIMENTAL TRIALS			
TASK COMMAND	**SSVER CHANGE REQUIRED**	**FEEDBACK PROVIDED**	**RESULTING CHANGE IN SQUARE FILL COLOR**
red border	enhance	circle grows	turns red
blue border	suppress	circle shrinks	turns blue

Condition 2: Trials were randomized such that fifty percent of the trials delivered feedback consistently mapped with SSVER amplitude, as used in Condition 1. The other trials provided inaccurate (noncontingent) real-time amplitude feedback (circle size). The following mapping was used with these "control" trials:

CONTROL TRIALS			
TASK COMMAND	**SSVER CHANGE REQUIRED**	**FEEDBACK PROVIDED**	**RESULTING CHANGE IN SQUARE FILL COLOR**
red border	enhance	circle shrinks	turns blue
blue border	suppress	circle grows	turns red

During this control condition, subjects were aware that circle size would be an inaccurate source of feedback. The purpose of including this noncontingent feedback condition was to observe any changes that the absence of accurate feedback might produce in performance and EEG.

Following completion of the four blocks of trials, subjects completed a final debriefing questionnaire that addressed their strategies or techniques for self-regulating their SSVER and their assessment of different aspects of completing the color matching task (see Appendix B). The final experimental session lasted approximately two hours.

Data analyses. Scalpwide EEG, task performance data, and subjective questionnaire responses were collected to assess EEG topography, subject performance, and opinions regarding the experimental task.

Topographic Brain Mapping: Scalpwide EEG from 19 sites was processed off-line to identify topographic, frequency, or event-related changes corresponding to SSVER self-regulation. Trials that contained eye or body movements, or other recording artifacts, were excluded from this analysis. Fast Fourier transforms were performed on

remaining trials, processed as two-second epochs preceding each color step (corresponding to the 2-second beyond threshold requirement). SSVER enhancement and suppression trials were analyzed separately. Ensemble averages were derived separately for different categories of task and trial parameters (evoke versus suppress commands, correct versus incorrect responses, experimental versus control trials). A total of 79 artifact-free epochs were included in the analysis.

Task Performance Data: Performance in the two experimental conditions was compared by examining three measures. First, the average number of steps (color shade changes) made to complete the trials was calculated. At least two steps were required for all the trials presented in the final session. Averages greater than 2.0, then, reflect the subject making erroneous steps (e.g., modifying the SSVER in the direction opposite what was commanded, resulting in a step towards the wrong end of the color palette, and/or overshooting the commanded color; both error types necessitated additional steps to acquire the color match). The second measure was average time to complete the trial (subjects had a maximum of 30 seconds to complete each trial). The third measure was the average percentage of color matches successfully acquired in each condition.

Questionnaire Data: Subjective data collected through the debriefing questionnaires were compiled to be presented in tabular form.

Results.

Topographic brain mapping. The EEG power spectra that resulted from these recording sessions illustrated a clear and dominant peak at the 13.5 Hz evoking frequency. This suggests that the SSVER control demonstrated reflects subjects' self-regulation of a narrow frequency band rather than broad-band artifactual activities. Different topographical distributions were also observed for "enhance" versus "suppress" trials (Nasman, Ingle, Calhoun, 1995). The differences were primarily noted over the occipital scalp, at the 13.5 Hz evoking frequency (Figure 9). Task-related SSVER suppression was associated with an even and bilateral distribution of 13.5 Hz activity across the occipital scalp. By contrast, the 13.5 Hz frequency band was lateralized to the left occipital hemisphere during SSVER enhancement. These patterns were absent or attenuated for incorrect color steps.

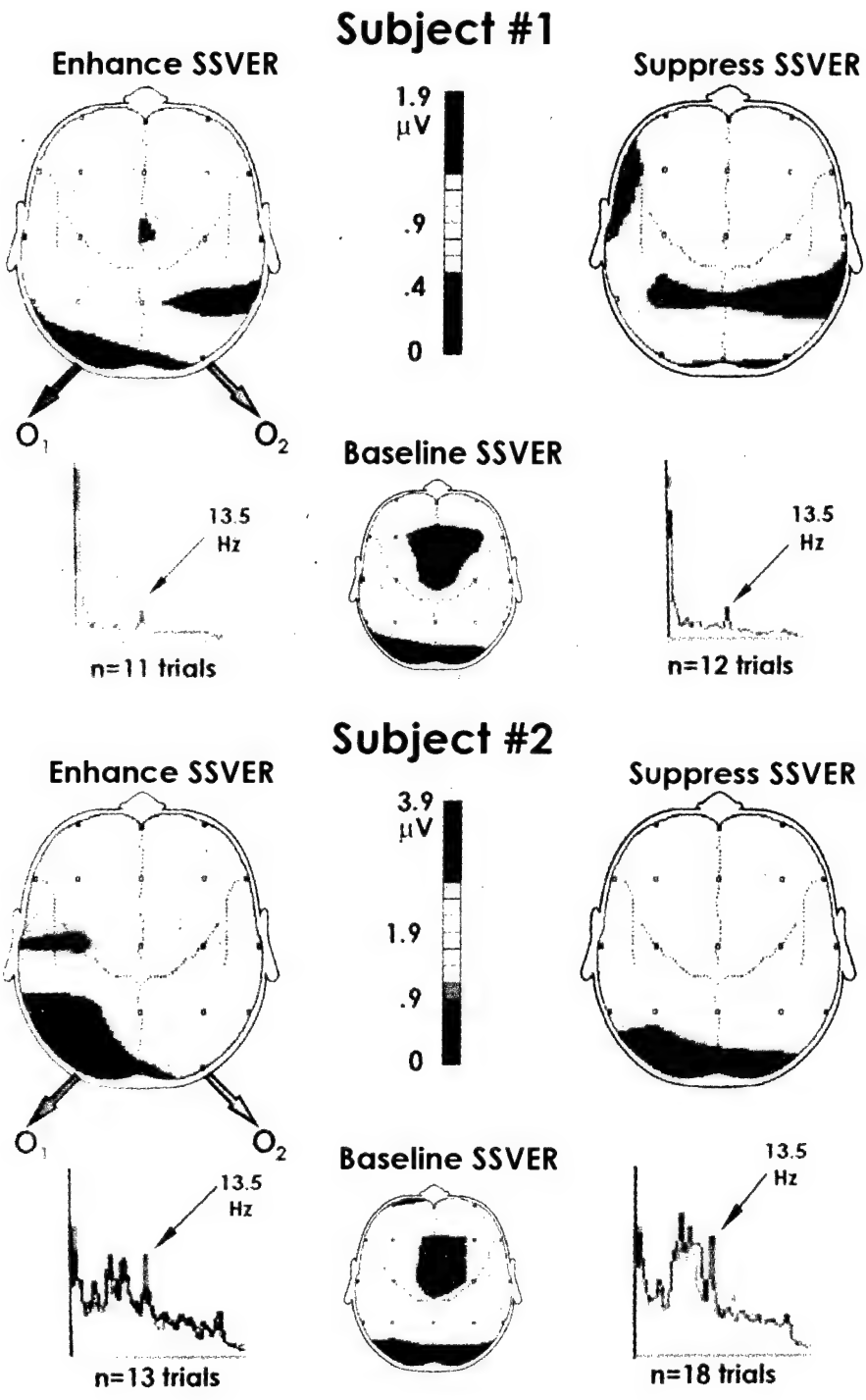

Figure 9a. Topographic maps of 13.5 Hz activity as recorded during task-related enhancement and suppression for Subjects 1 and 2.

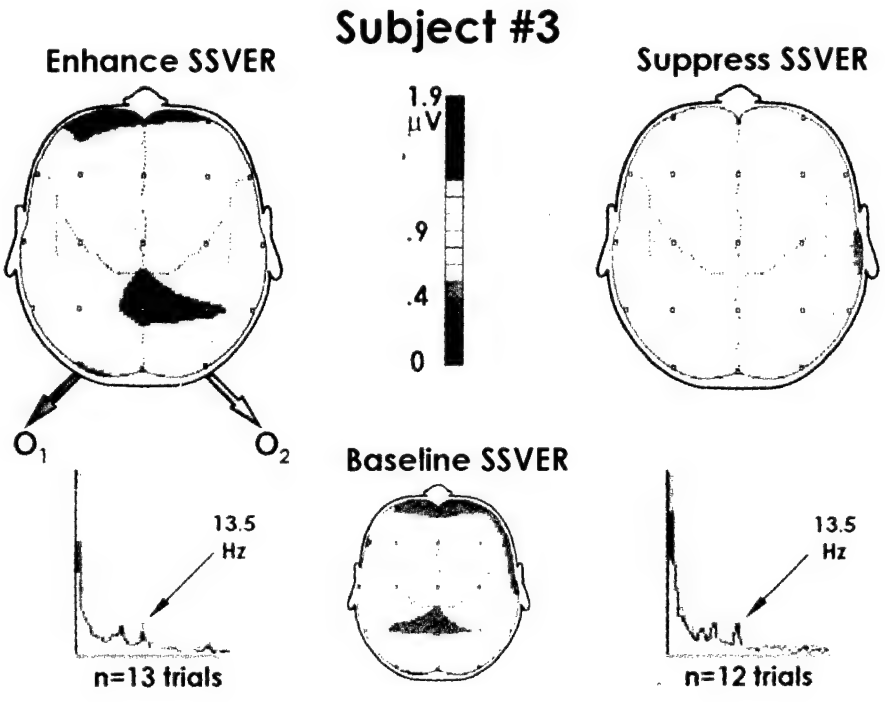

Figure 9b. Topographic maps of 13.5 Hz activity as recorded during task-related enhancement and suppression for Subject 3.

Task performance. Average trial scores and standard deviations (based on 24 trials per condition, per subject) are shown in Figure 10 for each of the three task performance measures. The percentage of color matches acquired were generally less than that recorded during the last three training sessions (where an 80% average was prerequisite to the final experimental session). This performance decline was probably due to distractions caused by the scalpwide EEG recording used in the final session. Also, subject's performance on the color matching task was not as good as that observed in other task paradigms using EEG-based control (Calhoun and McMillan, 1996). This probably reflects the more stringent control settings used in the present study to facilitate collection of scalpwide broad-band EEG during sustained epochs of SSVER enhancement and suppression. With different settings (e.g., reducing the duration requirement to one second), task performance would improve. Although the control algorithm used in the present study is not optimized for task performance, its use demonstrates that subjects can sustain SSVER modifications for more than two seconds.

Subject	Condition	Number of Steps	Trial Time	% Matches
1	Experimental	2.87 (+/-1.14)	22.0 (+/-8.7)	54%
	Control	3.36 (+/-1.21)	23.4 (+/-9.0)	50%
2	Experimental	3.00 (+/-1.21)	15.8 (+/-9.4)	79%
	Control	4.17 (+/-1.97)	24.2 (+/-8.6)	38%
3	Experimental	2.83 (+/-1.15)	14.0 (+/-7.9)	88%
	Control	4.58 (+/-2.57)	20.2 (+/-9.2)	58%

Figure 10. Task performance. Average trial scores (+/- standard deviation) based on 24 trials per condition, per subject.

Even though the task performance data recorded in the present study are not an accurate reflection of how subjects could perform this EEG-based control task with optimal parameter settings, these data are useful in comparing the two experimental conditions. For all three subjects and on all recorded measures, performance was better with the experimental condition in which the feedback mapping was identical to that used in training. For the control condition in which SSVER feedback was inconsistently mapped to the color step, task performance was degraded, reflected in a decrease in the percentage of successful color matches and an increase in the number of steps made and trial completion time.

Debriefing questionnaire. Subject responses to the debriefing questionnaire are provided in Appendix B. The responses indicate the subjects felt confident in their ability to perform the color matching task by self-regulating their SSVER. On a question that asked them to rate their present overall ability to do the task on a scale from 0 (no control) to 10 (perfect control), subjects gave ratings of "7" (Subject 2) and "8" (Subjects 1 and 3). On questions addressing what strategies or techniques they used to perform the task, the subjects mentioned visualization and focusing attention on specific areas of the task display. The ratings comparing the difficulty of learning, initiating, sustaining, and stopping an enhanced SSVER versus a suppressed SSVER varied. Results show that the subjects always found one of the two processes (enhancing versus suppressing the SSVER) to be harder -- which one, however, differed on an individual basis.

Conclusions/Discussion

Neural mediation established. Peripheral mediators (e.g., broad-band eye or muscle artifacts) are unlikely with an EEG-based interface employing self-regulation of a narrow-band frequency, the SSVER to an evoking stimulus. Moreover, the performance data supports the hypothesis that SSVER self-regulation is a nontrivial, neurally mediated, and learned phenomenon. In the control condition that presented trials in which the feedback was not systematically related to the direction of change in the SSVER amplitude, performance was degraded for all three performance measures. If neural self-regulation is either a trivially-mediated or a highly adaptive phenomenon, task performance would not have shown a consistent degradation in performance across measures and for all subjects. Rather, the performance data support the conclusion that the neural response is learned and that trained feedback association is critical.

The scalpwide EEG data also provide evidence that SSVER self-regulation is neither trivially mediated nor spuriously achieved. Topographic maps of baseline and task-related records show SSVER activity over the occipital scalp as well as over the right fronto-central cortices. Moreover, the occipital SSVER amplitude gradients showed differences reliably related to specific task requirements to enhance or to suppress the bipolar SSVER control signal.

Hemispheric-based neurological mechanism suggested. It is well beyond the scope of the present effort to definitively establish the neurophysiological basis for SSVER self-regulation. The specific objective of the present study was to identify task and system event-related changes in brain electrical activity recorded scalpwide during SSVER self-regulation. The topographic data showed clear hemispheric differences for occipital evoked response frequency distributions recorded during SSVER enhancement versus suppression. These effects are consistent with the possibility that SSVER self-regulation involves mediation of the SSVER between the two bipolar (differential) recording sites. Moreover, the data from the second pilot study suggest that SSVER amplitude variation during EEG-based control is probably the result of some combination of both signal phase and amplitude variation.

Use of bipolar signal recording may increase the flexibility of system design with respect to individual cognitive strategies. However, it is also possible that the bipolar recording may facilitate a strategy based on manipulating hemispheric differences, even though there is a more optimum alternative strategy based on monopolar or other recording derivations. In that it is impossible to know whether the existing bipolar recording methodology is an asset or a hindrance to optimal learning and/or performance, alternative recording methodologies for EEG-based control should be examined.

OUTSTANDING ISSUES AND RESEARCH QUESTIONS

Operator Issues

Individual differences may be less of a problem in SSVER recording, compared to other brain electrical activity, for use in EEG-based interfaces. Because the SSVER is a primary sensory response to an exogenous stimulus, it is recorded very reliably over the primary occipital cortex. In this laboratory, it also has been demonstrated that the SSVER, as well as task-related changes in its amplitude, may be recorded at other (e.g., frontal, central) sites along the midline scalp. This is useful to know, in the event that future applications require multiple scalp recordings to support one or more signal controls or parameters.

To the extent that inter-hemispheric differences in SSVER timing and/or amplitude reflect learned strategies, it may be useful to observe their development over training and exposure. Additionally, the ability to maintain SSVER self-regulation skills over time has not been systematically evaluated. Perhaps even more important to application issues is whether operators can exercise SSVER self-regulation with an EEG-based interface in complex task environments where there are concurrent tasks to be performed and associated distractions.

Design Issues

It is recommended that experimentation continue to evaluate time-locked, task related effects of neural self-regulation on related cognitive and brain processes. Candidate variables to examine include: hemispheric dominance, phase versus amplitude modulation, phase versus amplitude feedback, attentional manipulations, "trivial" mechanisms (e.g., gaze, contrast or edge effects), and effects on related and unrelated brain processes and cognitive operations. Various evoking stimulus modalities (visual, tactile, etc.) should be compared. The results of these investigations may provide insight as to how to differentiate between intentional and unintentional EEG changes, improve the precision, reliability and speed of control, and permit multi-channel control.

The color matching task and associated procedures used in the study proved acceptable in terms of task performance, subjects' subjective opinion, and delineation of sustained epochs of SSVER modifications for data analyses. However, performance on the color matching task during the experimental session, which involved scalpwide data collection, was degraded compared to that recorded in the final training sessions. This result, coupled with the contamination of numerous epochs by noise from eye movements, significantly reduced the number of data samples suitable for analysis. For

future experimental application of this task, it is recommended that multiple sessions be conducted with the scalpwide recording system in place, so that subjects can become more accustomed to its presence. Further, it is suggested that the task display be reduced in size so as to minimize the magnitude of any eye movements. The strategy employed by some subjects to focus eye position on specific areas of the task display while self-regulating the SSVER also warrants further evaluation to determine if eye position or a task display variable is a factor in subjects' SSVER control.

SUMMARY

Although additional research is required to fully understand the neuro-cognitive basis for direct brain interfaces, the research presented in this report sheds light on the neural mechanisms of SSVER self-regulation. For example, the use of amplitude modulation, phase modulation, and their combination was clearly demonstrated in these data. The findings reported herein also illustrate that brain electrophysiological recording provides noninvasive access to neural events that occur during SSVER self-regulation. Information acquired on signal alterations, as a result of self-regulation, may provide the basis for improved system control. Real-time monitoring of various neuropsychological parameters of neural self-regulation may enable an adaptive EEG-based interface, increasing the accuracy and precision of system operation and control. To the extent that identified neural activities provide an objective measure to track improvement in performance, research efforts along these lines may also provide a means to greater efficiency in operator training.

Real-world application of EEG-based interfaces will certainly begin before this new technology is explored comprehensively within the laboratory. Nevertheless, basic and applied research, testing, and evaluation in the laboratory must continue to support the development of more efficient and reliable methodologies and systems. Even as applied systems are conceived and implemented, laboratory and applied observations will provide essential research and development support in parallel. Research concerned with the nature of brain electrical events that take place during the exercise of EEG-based interfaces is key to optimizing their implementation and application.

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APPENDIX A

SUBJECT INSTRUCTIONS: Color-matching Task

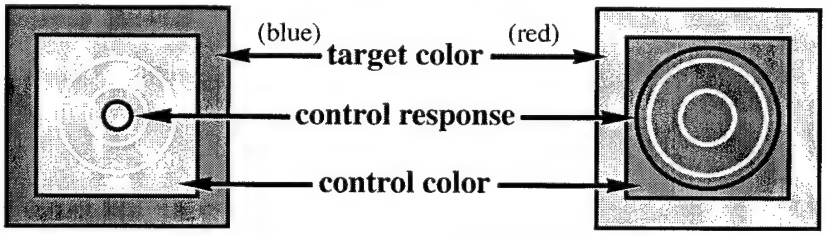
In this experiment, you will be tested for your ability to control a color-matching task by modifying your brain's response to a flashing light. The flashing light will be presented across a large projection screen. The task display will be presented in the center of the projection screen; you must attend to this display in order to do the task.

The task display is presented as a square. The goal of the task is to match the fill color of the inner square with that of its border. **The border color is your TARGET color.** The inner square color will change in response to the strength of your brain's response to the flashing white projection screen.

- **RED target** shades designate that you should enhance your brain's response
- **BLUE target** shades designate that you should suppress your brain's response.

There are several shades of each color. You should modify your brain's response in the direction designated by the target color, and you must continue until the color shade of the inner box matches that of the border.

Within the square are three circles. There is one black circle; the size of this circle will change in proportion to the strength of your brain response. As your response increases in strength, the black circle will grow larger; as your response decreases in strength, the black circle will become smaller. If your goal is to reach a red target color, you will attempt to make the black circle larger. If your goal is to reach a blue target color, you will attempt to make the black circle smaller.



The white circles designate control thresholds. When the **black circle grows** larger than the outermost white circle, this means you have achieved the response level necessary to produce a **color change toward red**. If the **black circle shrinks** and becomes smaller than the innermost white circle, this means you have reached the low response level needed to produce a **color change toward blue**.

Note that you must hold the black circle beyond the appropriate threshold for a specified period of time (0.5 - 2.0 seconds) in order to produce a single color step/shade change. The

experimenter will tell you about your required "hold" duration prior to each training or test session. If you fail to maintain your response level such that the black circle changes direction and crosses back over both thresholds (white circles), this will re-set the computer clock to zero and a new "hold" period will begin. (Crossing temporarily into the "neutral" zone between thresholds does not force the clock to re-set.)

As you maintain your desired response level, the color of the innermost box will step through consecutive shades of color approaching the target color. After you achieve the desired color match, you must return the black circle to its "neutral" zone between the two white circles. You must accomplish this within the designated "hold" time. If you fail to reach the neutral zone in that time, the color of the innermost box will continue to change and you will "overshoot" the intended color match. In order to succeed after an "overshoot," you must reverse course and restore the innermost box to the target color.

In each trial, you are allowed 30-60 seconds to achieve the color match and return the black circle to its neutral position. (The experimenter will instruct you as to your exact trial times during training and testing.) If you succeed, the task display will freeze and flash colorfully for a short time before displaying your trial score. If you fail to acquire the target in time, the trial will simply end ("trial timed out"). There will follow a brief scoring display, which you need not consider, attend, or memorize. This information is displayed only to assist the experimenter.

Trials will be delivered in series of 12 (total time = approximately 7 minutes). After each batch of 12 trials, a brief scoring display will summarize your performance in successful trials over the preceding trial series. Most of this information is presented to assist the experimenter. You need not memorize any of the scoring information, and you may elect to ignore it if you wish. However, you are encouraged to note the number of successful trials achieved, as this will help you to track your improvement over trial series and training sessions.

SCORE SUMMARY	
SUCCESSFUL TRIALS (%)	= 75% (9/12)
AVERAGE PERCENT CORRECT STEPS	= 95.6
AVERAGE TRIAL TIME	= 11.2
AVERAGE # OF SPURIOUS EVOKES	= 0.2
AVERAGE # OF SPURIOUS SUPPRESSES	= 0.1

Between each series of 12 trials, you will be given a 2-minute break to rest your eyes. Please alert the experimenter if you need to take a break at any other time, or if you are experiencing difficulties or discomfort. Please tell the experimenter if you are confused about the task, or if you need additional information about how it works.

APPENDIX B

QUESTIONNAIRE: COLOR-MATCHING TASK

==========

The purpose of this questionnaire is to collect information about your experience with brain-actuated control in the color-matching task. Your answers will be used to help us evaluate how our experimental subjects learn and achieve brain-actuated control. Your candid opinions and observations are a valuable contribution to this effort.

In some cases, we invite you to answer questions in your own words. Others are answered by selecting a specific response or checking a box that best corresponds to your experience. Feel free to contribute additional comments, however, and be as specific as possible.

Note: some of the questions below refer to "evoke" and "suppress" trials. "Evoke" trials were those in which you received a red command color and had to produce an increase in your brain response amplitude; if you succeeded, the black circle grew larger. "Suppress" trials were those in which you received a blue command color and had to decrease your brain's response amplitude, causing the black circle to shrink.

Feel free to request clarification if needed while completing this questionnaire.

==========

1. Describe your strategy(ies), technique(s), or approach to performing the color matching task. What did you do?

* **#1: I "visualized" where I wanted the real-time feedback ring to be. Thus, my attention was continually on the feedback ring and positioning my eye line-of-sight on the desired location. I watched the color steps/color command in my periphery. Also, I concentrated on relaxing; if I tensed up I couldn't do anything.**

  #2: Evoking→ I think about the color red & try not to think of anything else. Suppressing→ No actual thought, per se-- just a mental sensation of "blocking" activity in left hemisphere. (I don't feel anything-- I just describe it to myself in this way, to remind myself what to do.) [I] also try to be prepared to "back out" after a match, so as not to overshoot.

  #3: Evoke: looked on the right of the target
  Suppress: looked on the left of the target

* [Numbers 1-3 before comments and in tables refer to Subject 1, 2, and 3.]

2. Did/does your technique differ depending on trial type (color command)? ... did you do something different to "evoke" versus "suppress" your brain's response? Please be as specific as possible.

#1: For suppress trials, I concentrated on making the feedback ring a dot, which involved staring at the center of the square, and thinking "small." For evoke trials, I visualized a large black outer ring (and thus my eyes were directed outside the outer ring). Also, I visualized/thought about "pushing" the ring to make it grow bigger.

#2: Yes, evoking & suppressing are very different.
Evoking→ I think about the color red & try not to think of anything else.
Suppressing→ No actual thought, per se-- just a mental sensation of "blocking" activity in left hemisphere. (I don't feel anything-- I just describe it to myself in this way, to remind myself what to do.)

#3: I did the above consistently.

3. The following questions address your assessment of various aspects of performance in the color matching task.

(a) Do you feel you were/are more or less able to "evoke" (produce red) or "suppress" (produce blue)?

#1: yes
#2: Now I feel I'm better able to suppress. But in early training, this was harder.
#3: "Evoke" was easier.

(b) Indicate which process was harder based on the following criteria: **

	Evoking (red)	No different	Suppressing (blue)
To Learn	❶		❷
To Initiate	❶	❷	❸
To Sustain	❶		❷
To Stop		❶	❷

**Subject #3 responded to only one of the four inquiries

Comments, if any:

#1: [no response]
#2: My answers here are "in general"-- but these trends sometimes vary in different sessions or due to calibration effects.
#3: [no response]

4. Did/do your strategy(ies) or technique(s) change over the course of a test session? If so, in what way? Do you have any ideas about why this happens?

#1: For suppress trials, I concentrated on making the feedback ring a dot, which involved staring at the center of the square, and thinking "small." For evoke trials, I visualized a large black outer ring (and thus my eyes were directed outside the outer ring). Also, I visualized/thought about "pushing" the ring to make it grow bigger. Once color match [was] achieved, I visualized "letting go" to change the direction of the feedback ring.

#2: My strategies usually don't change over a single session--unless I'm having a lot of trouble & feel the need to try new strategies.

#3: My technique did not really differ [in] the course of the test sessions.

5. Did/do you find that your technique(s) or strategy(ies) change over the course of training? Please offer comments, if any.

#1: early on, tried to repeat thoughts used in flight task to evoke; this strategy, however, did not work.

#2: Yes. Now I know how it "feels," and I no longer have to use strategies like imagery or silent verbal command. (I do still think about the color red to evoke.)

#3: My technique did not change during the course of the training.

6. Please rate your present overall ability to do the color-matching task.

	0	1	2	3	4	5	6	7	8	9	10	
NO CONTROL								❷	❶ ❸			PERFECT CONTROL

Comments, if any: **[no responses]**

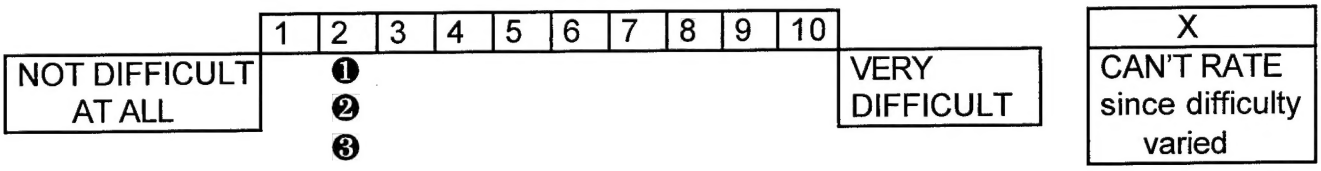
7. Concerning your present overall ability, please indicate the answer that corresponds best to your experience.

A) I always have to concentrate very hard.
❷ B) I usually have to concentrate very hard.
C) I sometimes have to concentrate very hard.
❶ ❸ D) I rarely have to concentrate very hard.
E) I never have to concentrate very hard.

Comments, if any: **[no responses]**

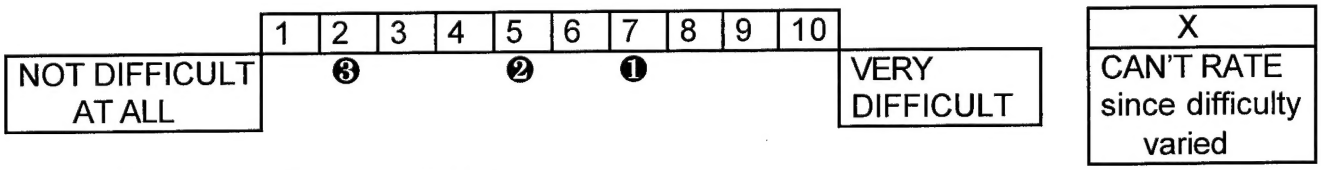
8. Questions (a) - (e) refer to how challenging you found specific aspects of performance on this task.

(a) Initiating the brain response to the neutral zone (to initiate task onset) was:



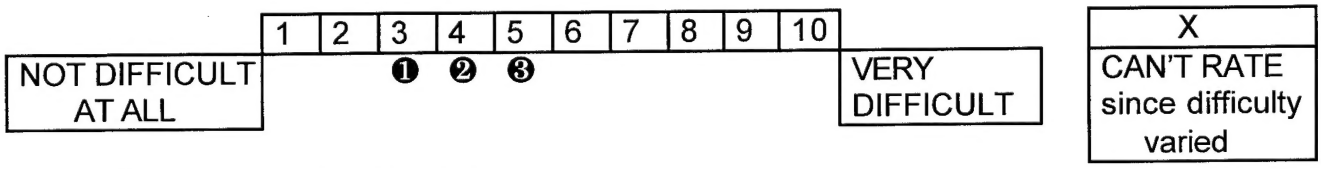
Comments: **[no responses]**

(b) Increasing the brain response in an "evoke" trial was:



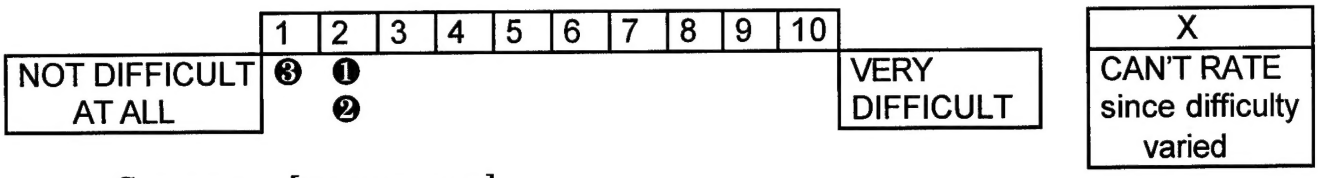
Comments: **[no responses]**

(c) Decreasing the brain response in a "suppress" trial was:



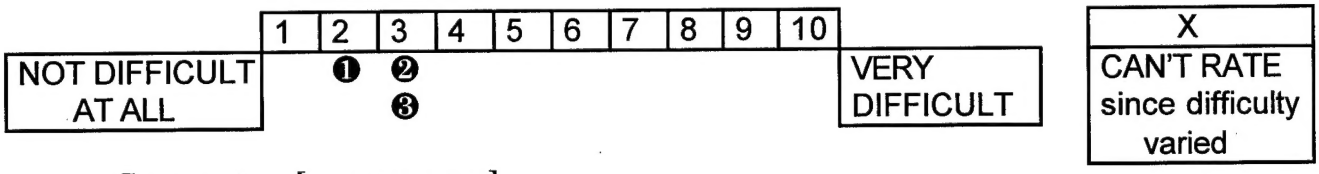
Comments: **[no responses]**

(d) Changing the brain response toward the neutral zone to close a trial after an "evoke" (red) match was:



Comments: **[no responses]**

(e) Changing the brain response toward the neutral zone to close a trial after a "suppress" (blue) match was:



Comments: **[no responses]**

(9) Were there any aspects of the task, or the task display, that you found confusing or difficult to interpret or understand? If Yes, please describe.

#1: No
#2: No
#3: No

(10) Do you feel the feedback circle is:

❷ (a) too sensitive (jumpy, fast)
❶ ❸ (b) about right
(c) too sluggish (dragging, slow)

Comments, if any: **[no responses]**

(11) Did/do you have any difficulty detecting color differences or color matches? If Yes, please describe.

#1: Yes, there were two shades of blue that I was typically confused as to whether I should evoke or suppress.

#2: No

#3: No

(12) Did/do you direct your visual attention toward any particular portion of the task display or screen at particular times during the task? If Yes, please describe specifically what you do, and when/why.

#1: Yes: at center during suppress, outside outer ring during evoke.

#2: Yes: I do tend to look at different areas of the box to evoke (border) vs. suppress (center).

#3: Yes: looked to right to evoke and left to suppress.

(13) Did/do you tense or move your eyes, muscles, or body during the task? If Yes, please describe specifically what you do, and when/why.

#1: Yes: some eye movement involved in changing direction of attention. At times I found myself staring, prohibiting eyes from blinking.

#2: Yes: some eye movement -- I do tend to look at different areas of the box to evoke (border) vs. suppress (center)

#3: Yes: moved eyes to right to evoke and left to suppress

(14) Were/are there any distractions during the course of the experiment (noise, temperature, etc.)? Were/are the scalp-attached electrodes distracting in any way? If Yes, please describe.

#1: No
#2: No
#3: No

15) Did/do you experience any of the following during the experiment: eye strain, headache, mental fatigue, physical fatigue, postural discomfort, or other discomfort? If Yes, please describe.

#1: No

#2: Yes: postural discomfort; some mental fatigue during final run; eye strain during last half of session.

#3: No

(16) Please provide any other comments you would like to make concerning this task or experiment, or concerning brain-actuated control. Possible topics include training, instructions, task parameters, calibration, recording procedures, and experimental procedures.

#1: [no response]

#2: Need to make calibration ongoing, adjustable to change over time.

#3: [no response]